Compressive creep behavior of paperboard in a cyclic humidity environment–exploratory experiment

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ABSTRACT *We examined the mechanosorptive behavior of two paperboards loaded with an edgewise compressive load while in an environment of changing humidity to determine whether creep rate and stiffness loss could be used to predict failure and to determine a theshold stress at which creep rate increases dramatically. All creep tests were performed in a unique apparatus developed and built at the Forest Products Laboratory. Cyclic humidities caused greater failure strain, faster strain rates, and earlier failures in creep tests. Creep rate and stiffness loss rate are directly related, and they appear to be good predictors of failure. This testing procedure has potential for determining the load-carrying ability of paperboard in uncontrolled environments.*

KEYWORDS
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Paperboard
Stiffness
Strain

Creep is a time-dependent deformation of a material under constant stress. Cellulosic materials undergo extensive, unexpected creep deformations in environments where the humidity changes. This behavior is called the "mechanosorptive effect" because it cannot be explained by the superposition of mechanical load response and sorption response (*1*).

Despite control systems and insulation, warehouses are often unable to eliminate cyclic humidity fluctuations caused by rapidly changing weather conditions. Figure 1 shows outdoor relative humidity (RH) for Madison. Wis., in February 1987, as measured by the National Weather Service. As a result of weather patterns and the lack of elaborate moisture control systems in the manufacture–transportation–storage cycle, most corrugated containers experience moisture sorption and, therefore, the mechanosorptive effect during their service lives.

In testing the performance of corrugated containers, Leake (*2*) found that cyclic relative humidity changes reduced container performance in ways that could not be predicted from tests under constant relative humidity. The aim of the study was to determine the effectiveness of using a medium of lower basis weight in containers. Edgewise compression tests (ECT) performed at constant relative humidities of 50% and 90% revealed no significant difference in the corrugated boards. However, containers made with a medium of lower basis weight experienced greater creep than containers made with heavier medium after only one relative humidity change, from 50% to 90%.

Byrd has performed the most extensive testing of paperboard and combined board during changing humidity conditions. In 1972, Byrd reported that uniaxial compressive creep tests of ECT specimens in environments of cyclic relative humidity produced greater failure strain, faster creep rates, and earlier failure than the same tests in constant relative humidity (*3*). Byrd and Koning reported that high-yield linerboards produced high creep rates (*4*). In 1984, Byrd reported that compressive creep rates of corrugated boards were 2-5 times greater than the predicted rates, based on the performance of the component materials (*5*).

I. Tension and compression properties for two paperboards tested in machine and cross-machine directions

Paper-board	Test	Direction[a]	Failure load, kN·m/kg	Strain, %	Stiffness, MN·m/kg	Squareness (MD/CD) Failure load kN·m/kg	Squareness (MD/CD) stiffness MN·m/kg
A	Tension	CD	30.4	4.35	3.36	...	...
	Compression	CD	15.3	0.91	3.18	...	...
	Tension	MD	99.9	3.77	9.76	3.3	29
	Compression	MD	327	0.50	10.03	21	32
B	Tension	CD	10.8	2.13	1.19	...	...
	Compression	CD	6.1	1.10	1.12	...	...
	Tension	MD	39.3	1.36	6.16	3.6	52
	Compression	MD	19.5	0.43	6.45	32	5.8

[a]CD - cross-direction; MD = machine direction.

objectives will increase our knowledge of the mechanosorptive effect. In turn, this knowledge will allow container designers to more effectively choose materials and design structural products.

Materials and methods

Both paperboards were made on a Formett Dynamique at 1800 rpm. These paperboards were wet pressed under line pressure and were dried under restraint on a cylinder at 100°C. Paperboard A was made from a sulfate pulp of bleached scotch pine (*Pinus sylvestris L.*) with a basis weight of 228 g/m^2 and a density of 754 kg/m^3. Paperboard B was made from a bleached chemithermomechanical pulp of spruce (*Picea abies L.*) with a basis weight of 215 g/m^2 and a density of **434** kg/m^3.

We performed tension tests on necked specimens at constant 50%RH in both the machine direction (MD) and cross-machine direction (CD) on a standard Instron machine equipped with a specially designed extensometer (*10*). Similarly, we performed compression tests on the FPL vacuum restraint apparatus (*11*) at constant 50%RH for both MD and CD compression.

Creep tests were conducted on an apparatus developed and built at FPL (*9*). The apparatus consists of a load frame. a means of lateral support, and a system for controlling relative humidity in a small environmental chamber. A previously developed vacuum restraint method (*12*) provided the lateral support necessary to prevent buckling under compressive load and hastened the equilibration of the specimen to relative humidity changes. The vacuum restraint system and load frame were located inside a small environmental chamber. The frame loaded the rectangular specimens through tabs attached to the specimen. A proportional flow control valve mixed dry and saturated air to be introduced into the environmental chamber. A microcomputer controlled applied load and chamber relative humidity, measured deformation and stiffness, and stored pertinent information during testing.

An extensional stiffness measurement was initiated by the computer, which specified that a sawtooth load pulse be applied by the load frame to the specimen. If a creep load was already applied to the specimen, the sawtooth load was superimposed on the creep load. Load, measured by a load cell, and deformation, measured by an extensometer riding on the specimen, were sampled by the computer. The computer performed a regression on the collected load–deformation data, whose slope was the current extensional stiffness of the specimen under test. The sawtooth load pulse had a magnitude of ±0.2 kN/m and a duration of 0.5 s. The extensional stiffness measurement was nondestructive.

All creep loads were compressive and were applied in the cross direction. We found that 38–43% of the short-term compression strength at 50%RH was the maximum creep load each paperboard could sustain for at least three relative humidity cycles. Creep loads higher than this produced immediate failure upon moisture cycling. Preliminary tests had shown that 23% load did not produce failure; therefore, no tests were performed below this level.

The creep tests were conducted with sinusoidal humidity cycles that had a mean of 70% RH and an amplitude of 20% RH (i.e., a minimum of 50% RH and a maximum of 90%RH), and 10-min periods. Stiffness and deformation were measured at 50% and 90% RH. Ten relative humidity cycles were performed before the load was applied to equilibrate the specimen and obtain baseline values.

We also performed creep tests at constant 50% RH under the maximum sustainable creep load in cyclic relative humidity changes.

Results and discussion

Short-term tension and compression tests

Table I shows paperboard properties in short-term tensile and compressive testing at 50% RH. As expected, extensional stiffness values measured from tensile and compressive tests were nearly equal; strain to

II. **Results of compressive creep tests**

Paperboard	Load[a] %	End test time[b], h	stiffness[c], MN·m/kg Initial	Final	Final strain, %	Minimum stiffness rate,[d] kN·m/kg/h	Minimum strain rate, %/h
			Cyclic, failure				
A	38	0.82	4.15	2.33	-1.42	-1,1420	-1.21
	38	0.66	4.15	2.35	-1.45	-1,548.0	-1.64
	33	39.02	4.60	2.53	-1.87	-11.4	-0.02
	33	2.97	4.38	2.42	-1.66	-260.6	-0.37
	29	24.72	4.26	2.16	-1.66	-7.1	-0.02
	29	1.45	4.00	2.38	-1.44	-345.7	-0.67
	29	4.89	4.06	2.29	-1.61	-92.2	-0.14
B	43	1.31	1.37	0.53	-3.00	-284.6	-1.83
	43	0.82	1.33	0.60	-259	-368.1	-2.61
	37	3.66	1.33	0.49	-3.38	-57.7	-0.48
	37	2.28	1.26	0.50	-3.26	-101.7	-1.04
	37	1.47	1.27	0.64	-2.30	-131.9	-1.11
	33	20.12	1.40	0.51	-3.43	-7.1	-0.09
	33	7.95	1.31	0.45	-3.24	-27.7	-0.14
	29	76.24	1.13	0.39	-3.37	-1.1	-0.01
	29	21.06	1.31	0.43	-3.11	-4.8	-0.05
			Cyclic, no failure				
A	25	116.79	4.10	284	-1.14	-0.1	~0
B	23	82.38	125	0.59	-223	-0.5	~0
			Constant, no failure[e]				
A	38	89.44	3.87	3.73	-0.30	~0	~0
B	43	23.68	1.31	1.13	-0.40	~0	~0

[a]Percentage of CD compressive failure load (Table I).

[b]For cyclic, failure tests-time of failure. For other tests—timetest ended.

[c]Initial, average extensional stiffness at 50% RH prior to load application. Final, extensional stiffness at 50% RH just pior to failure.

[d]Minimum slope of stiffness—timecurve as calculated by linear regression of stiffness at 50% RH of $\geq$ 10 consecutive data points. Minimum strain rate defined similarly.

[e]RH 50%.

failure was much higher (2-10 times) in tension than compression, and maximum load was higher in the cross direction.

Paperboard B had significantly lower strength and extensional stiffness than Paperboard A. The compressive failure strain for Paperboard B, for both directions, was similar to the compressive failure strain for Paperboard A. However, the tensile failure strain for Paperboard B, for both directions, was lower than that of Paperboard A.

Compressive creep tests

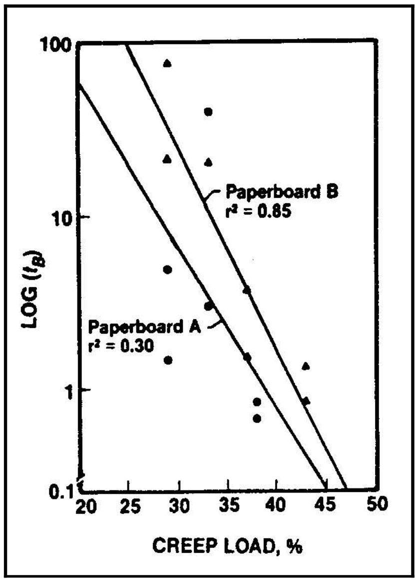
Figure 2 shows strain and stiffness as a function of time as measured during a compressive creep test in a cyclic environment for a Paperboard B sample at 29% of the maximum 50% RH load listed in Table I. Specimens in some tests did not experience tertiary creep because failure occurred during primary or secondary creep. The point at which the load was applied is indicated.

The large creep deformation shown in Fig. 2A is not unusual. The creep failure strain for this sample was more than three times the failure strain measured in short-term compressive tests at 50% RH.

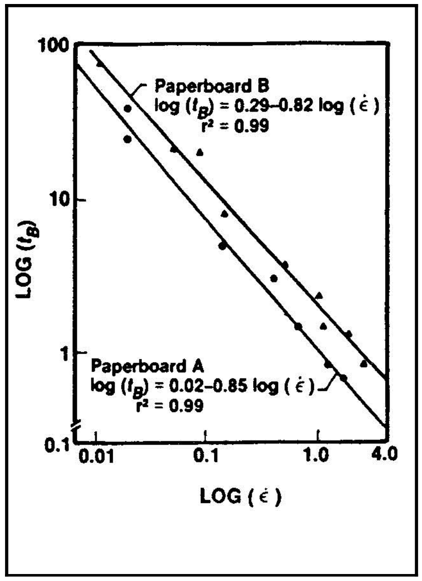
Figure 2B demonstrates the uniqueness and utility of our apparatus. During the creep test, not only can we monitor deformation, but we can also nondestructively measure specimen extensional stiffness *in situ.* We have found that significant extensional stiffness loss generally accompanies large creep deformation. Stiffness declined in all creep tests in which specimens ultimately failed. The general similarity of Figs. 2 A and 2B suggests a relationship between extensional stiffness and deformation.

Results of the creep tests are listed in **Table II,** which is divided into three sections: cyclic relative humidity tests in which specimens failed,

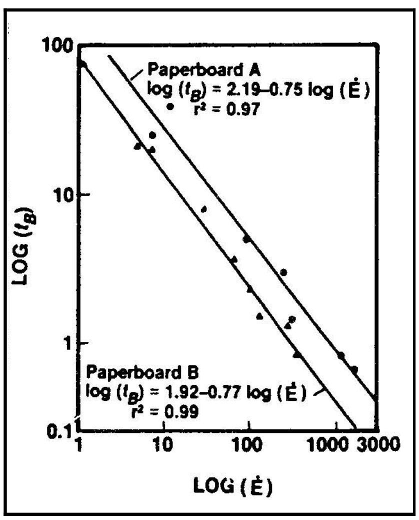
3. For both paperboards, the wide scatter of data points hampered our ability to use load level to predict time to failure with statistical significance (ML89 5587).



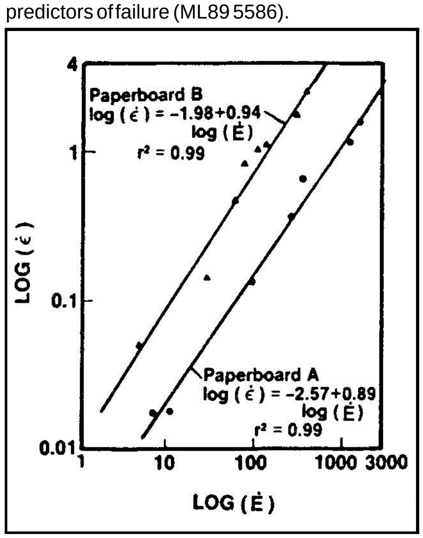
4. Minimum creep rate allows an accurate prediction of failure (ML89 5588).



5. Minimum stiffness loss rate allows an accurate prediction of failure time (ML89 5585).



6. Both minimum creep rate $\dot{\epsilon}$ and minimum extensional stiffness loss rate $\dot{E}$ are equally good predictors of failure (ML89 5586).



cyclic relative humidity tests in which specimens did not fail, and constant relative humidity tests. No constant relative humidity tests resulted in specimen failure. All creep tests were performed in the cross direction. Specimens in tests with a high percentage of load survived only a few cycles. In these tests, minimum strain rate and minimum stiffness rate simply refer to the linear regression of the available data points. Minimum strain rate and minimum stiffness rate did not necessarily occur at the same time during the test, despite the general correspondence demonstrated in Figs. 2A and 2B.

A comparison of Tables I and II shows that failure strain was much higher for the cyclic relative humidity creep test (Table 11) than for the short-term, (CD) compressive tests, (Table I). Paperboard A failure strains were 1.5–2 times the short-term CD compressive failure strain, and Paperboard B failure strains were about 3 times the short-term (CD) compressive strain. Final extensional stiffness for the paperboards ranged from one-third to two-thirds of the initial specimen stiffness. Minimum strain rate and minimum extensional stiffness rate were much smaller at low stress than at high stress, and these rates approached zero in tests in which specimens did not fail.

As illustrated in Table 11, all specimens that ultimately failed also lost extensional stiffness. Paperboard A experienced a higher rate of stiffness loss than Paperboard B, but this was not necessarily a detriment to Paperboard A because it was initially much stiffer than B. Note that Paperboard B did not experience a high rate of stiffness loss before failure. At loads much higher than those tested, we anticipate that failure would occur before the specimen reached 90%RH on the first humidity cycle.

Figure 3 depicts time to failure as related to percentage of load. Although the data points are scattered, which is typical of most creep data, the figure generally shows that the logarithm of time to failure increased linearly as the load was decreased. This relationship is observed in many materials. Both paperboards showed an order of magnitude reduction in "durability" over the range of 25% to 30% load.

Prediction of failure time

The acceptable loads were much lower than might be expected. If either of the paperboards was expected to experience changing humidities of reasonable magnitude, its acceptable load level would be <30% of the short-term compressive strength at 50% RH. Alfrey (*13*) pointed out the difficulty of using load as a predictor of failure. Seemingly identical specimens subjected to identical loads have a wide scatter of the data for time to failure. Alfrey pointed out that the process leading to failure should be able to predict failure.

Figure 4 shows that minimum creep rate may be a predictor of failure. Using the Monkman-Grant equation (*14*), a linear regression of these points gave the following results.

Paperboard A:

$$\log(t_B) = 0.02 - 0.85 \log(\dot{\epsilon})$$

$$r^2 = 0.99 \qquad (1A)$$

Paperboard B:

$$\log(t_B) = 0.29 - 0.82 \log(\dot{\epsilon})$$

$$r^2 = 0.99 \qquad (1B)$$

where

t_B = time to failure

$\dot{\epsilon}$ = minimum compressive creep rate.

Alfrey's point is validated by Figs. 3 and 4. Although the data were widely scattered when relating time to failure and load (Fig. 3), the points became much more coherent when we used a property from the process that preceded failure—in this case, minimum creep rate.

Figure 5 shows that extensional stiffness loss during creep may also be a predictor of failure. Using a Monkman-Grant-type equation, we determined the following.

Paperboard A:

$$\log(t_B) = 2.19 - 0.75 \log(\dot{E}) \qquad r^2 = 0.97 \tag{2A}$$

Paperboard B:

$$\log(t_B) = 1.92 - 0.77 \log(\dot{E}) \qquad r^2 = 0.99 \tag{2B}$$

where

$\dot{E}$ = minimum extensional stiffness loss rate.

Figures 3-5 show the advantage of using the process leading to failure as the predictor of failure. Prediction of failure using applied load would require additional testing and statistical analysis because of the wide scatter of data points. However, in these same tests, creep rate and stiffness loss rate proved to be highly accurate predictors of failure. Also, there is a practical advantage of using these properties to predict failure. If the test has not yet reached the minimum level of the creep rate of stiffness loss, then a prediction of failure based on these properties will be conservative—in other words, it will be a prediction of an earlier failure, If the test has reached the minimum levels, then failure can be accurately predicted.

Minimum creep and stiffness loss rates were highly correlated, as shown in **Fig. 6.** As a result, minimum compressive creep and stiffness loss rates would appear to be equally good predictors of failure. The regression lines were as follows.

Paperboard A:

$$\log(\dot{\epsilon}) = -2.57 + 0.89 \log(\dot{E}) \qquad r^2 = 0.99 \tag{3A}$$

Paperboard B:

$$\log(\dot{\epsilon}) = -1.98 + 0.94 \log(\dot{E}) \qquad r^2 = 0.99 \tag{3B}$$

Conclusions

The compressive creep behavior of two paperboards subjected to cyclic humidity was examined. The testing equipment is unique, and it provides accurate, reproducible results. several conclusions can be drawn from this work:

1. For the materials tested, the acceptable load level in cyclic humidity environments was less than 30% of the short-term compressive strength, measured at 50% RH.
2. Failure strains in cyclic humidity environments are as much as two to three times greater than short-term maximum compressive strains at 50% RH. Byrd (*5*) reported that this ratio is even larger in combined board.
3. Paperboard experiences large extensional stiffness loss during creep in cyclic humidity environments.
4. Extensional stiffness loss rate and compressive creep rate are good predictors of failure.
5. Extensional stiffness loss rate and compressive creep rate are directly related.
6. This method of testing is a potential tool for determining the load-carrying ability of paperboard in uncontrolled environments. ❑

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